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Challenges in Interconnection and Packaging of Microelectromechanical Systems (MEMS)

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Abstract

Integrated circuit packaging and their testing is well advanced because of the maturity of the IC industry, their wide applications, and availability of industrial infrastructure. [1,2] This is not true for MEMS with respect to packaging and testing. It is more difficult to adopt standardized MEMS device packaging for wide applications although MEMS use many similar technologies to IC packaging. Packaging of MEMS devices is more complex since in some cases it needs to provide protection from the environment while in some cases allowing access to the environment to measure or affect the desired physical or chemical parameters. Microscopic mechanical moving parts of MEMS have also their unique issues. Therefore, testing MEMS packages using the same methodologies, as those for electronics packages with standard procedures might not always be possible especially when quality and reliability need to be assessed. Single MEMS chip packaging approaches and their limitations in the packaging of high performance MEMS will be reviewed in this presentation and also identifies a need for a systematic approach for this purpose.

MEMS package reliability depends on package type, i.e. ceramic, plastic, or metal, and reliability of device. The MEMS device reliability depends on its materials and wafer level processes and sealing methods used for environmental protection. MEMS quality and reliability challenges are discussed and needs for study in these areas are identified.

Keywords

Interconnections, Packaging, Commercial-Off-The-Shelf, Microelectromechanical Systems, MEMS, COTS, Quality Assurance, Reliability, and Space Environment.

Introduction

MEMS chip mounting or bonding methods and MEMS chip-substrate interconnection techniques are seriously considered in MEMS packaging (which includes stress decoupling, chemical passivation, electrical shielding and interconnections). MEMS active elements are in direct contact with environmental physical and chemical parameters, which degrade the reliability of the overall package. MEMS have shown significant promise in the last decade for a variety of applications such as sensors for air-bag deployment (accelerometers), pressure sensors, accelerometers, microgyros, chemical sensors, artificial nose, etc. Standard semiconductor microelectronics packaging protects the integrated circuits (IC) from the harsh environment, provides electrical communication with the other parts of the circuit, facilitates thermal dissipation efficiently, and imparts mechanical strength to the silicon die. Microelectronics packaging involves wafer dicing, bonding, lead attachment/interconnects, encapsulation to protect from the environment, electrical integrity, and package leak tests to assure reliable IC packaging and interconnect technology.

Applications of MEMS sensors and their packaging technology have been under rapid development in the last decade or so. Thick and thin film technology can be used to produce an electronic circuit for sensor adjustment, (nulling, offset, calibrating sensitivity) temperature compensation and signal processing. The MEMS package includes a MEMS device and a signal conditioning electronic circuit. The electrical signal from the MEMS sensors is mainly low level, and therefore, very sensitive to some kind of interference. The electronic circuit has significant influence on the accuracy and long term stability of the MEMS package.

Active elements or microstructures in MEMS devices often interface with the hostile environment where package leak tests and testing of such devices using chemical and mechanical parameters will be very difficult and expensive. Packaging of MEMS is complex as the package protects the device from the environment and the microstructures must still interact with the same environment to measure or affect the desired physical or chemical parameters. Most of the silicon circuitry is sensitive to temperature, moisture, magnetic field, light, and electromagnetic interference. The package must then protect the on-board silicon circuitry while simultaneously exposing the microsensor to the effect it measures.

MEMS technology has major applications in developing microspacecraft for space systems provided the reliability of MEMS packaging/interconnect technology is sufficiently addressed. This MEMS technology would eventually miniaturize many of the components of the spacecraft to reach the NASA's goal of building faster, cheaper, better, safer, smaller, and more reliable spacecraft to explore space more economically and effectively.

One of the methods used is to create through wafer vias that allow access to each of the active signal lines on the device wafer. These vias can then be connected to a metal line that runs to a bond pad at the periphery of the MEMS chip. The pad is then wire bonded or solder bumped, to allow one to use a flip chip attachment of the MEMS die to a package substrate. The viable option for fabricating through wafer vias in a high volume-manufacturing environment is bulk micromachining. These vias will consume a fairly large portion of the available silicon real estate. For low I/O count devices, this requirement can be managed, however, for more sophisticated sensors or multi-sensor systems, this option may become a technical challenge.

Hermetically sealed packages require that the active signal lines travel through the seal region to make electrical connection to the device. This can require additional processing, which increases the cost and complexity of the sensor. Conventional single MEMS-chip packaging frequently limits the over all density and performance of MEMS systems. These limitations may be overcome by a variety of customized multi-MEMS chip-packaging approaches that provide short and dense chip-to-chip to interconnections. The challenge to the MEMS sensor manufacturer is to develop packaging technologies that meet all the necessary performance and reliability criteria while keeping assembly costs to a minimum. In the case of MEMS, the packaging needs to be considered very early in the design cycle, and adequate consideration must be given to the end use environmental conditions in which MEMS will be placed.

Research and development of MEMS has shown a significant promise for a variety of commercial applications. Some of the MEMS devices have potential to become the commercial-off-the-shelf (COTS) components. Aerospace requires more sophisticated technology development to achieve significant cost savings if they could utilize COTS components in their systems.

MEMS Device Level Reliability Issues

MEMS devices are usually fabricated at microscopic level. A typical device level process flow before packaging involves surface micromachining or bulk micromachining of wafers, formation of desired pattern along with various bonding techniques followed by subsequent interconnection and cavity sealing in package enclosure. Surface micromachining is a technique for fabricating three dimensional micromachined structures from multilayer stacked and patterned thin films. [3-7] In bulk micromachining, a bulk of wafer is wet or dry etched to fabricate micromachined structures in either silicon crystal or deposited or grown layers on silicon. Bonding is another key process that is used during the fabrication which include field assisted thermal bonding, thermal fusion bonding, eutectic bonding, etc.

Reliability of surface micromachined device depends on materials used and processes employed to build-up by thin film processing, etc. Generally, there are large residual stresses induced in thin films that affect the performance of device to a variable degree. For example, residual stresses in thin film with improper adhesion could cause delamination. [8-10]

Bulk micromachined devices have their own unique reliability issues. These include sharp corners from anisotropic etching, adhesion issues as discussed above and generally poor quality due to an non-optimized process from many process steps. [9] In contrast, polymer micromachined devices show very high bond strength and low residual stresses. Reliability issues include poor mechanical strength, inability to perform hermetic seals, and use under high vapor pressure. An example of this technology is LIGA (Lithographie, Galvanoformung, Abformtechnik) which stands for lithography, electroplating, and molding that enables the structure of bulk micromachining with feature characteristics of micromachined devices. [11]

Different bonding techniques are used for microsensors attachment each with their unique characteristics. For example, glass to silicon joining can be accomplished by field assisted thermal bonding also known as anodic bonding, electrostatic bonding, or the Mallory process. [12] Anodic bonding has the advantage of being a lower temperature process with a lower residual stress and less stringent requirements for the surface quality of the wafers. In silicon fusion bonding, no intermediate layers needed, therefore it simplifies device fabrication. [13] Although eutectic bonding was demonstrated [14] in bare silicon against gold covered silicon, or gold covered silicon against gold-covered silicon, there are some considerable disadvantages associated with Au/Si (gold/silicon) eutectic bonding. It is difficult to obtain complete bonding over large areas and native oxides prevent the bonding to take place. Eutectic preform bonding is reported to introduce substantial mounting stress in piezoresistive sensors, causing long-term drift due to relaxation of the built-in stress. [5,6]

After wafer bonding process and interconnection, MEMS devices are generally hermetically sealed within a package. [5,6] The hermeticity is important for physical protection and in some cases for the device performance. For example, damping characteristics of a resonator in a pressure sensor is critically dependent on a good hermetic seal. In addition, the vacuum reference of an absolute pressure sensor, and the cavity of a pneumatic infrared sensor and microgyro package are all critically dependent on a good hermetic seal package. Minami et al, [15] used nonevaporable getters built into the microdevice to control the cavity pressure for critical damping of packaged micromechanical devices and similar approaches were proposed in. [16-19] Organic materials are not good candidate materials for hermetic packages. For almost all high-reliability applications, the hermetic seal is made with glass or metal. Silicones do not act as a moisture barrier; the exact mechanism by which they protect the die when applied, as a surface coat that is not yet well-understood. [20]

Reactive sealing and sealant films are other methods with highest performance characteristics especially for sealing process for pressure sensors. Recently, the first commercial absolute poly-silicon pressure sensor, incorporating a reactively sealed vacuum shell, was introduced for automotive applications. [21] Another application of the sealed surface shells is the vacuum packaging of lateral surface resonators. Most resonator applications share a need for resonance quality factors from 100 to 10,000. However, the operation of comb-drive microstructures in ambient atmosphere results in low quality factors of less than 100 due to air damping above and below the moving microstructure. Vacuum encapsulation is thus essential for high Q applications. [22]

Compatibility Issues

If the micromachined structures are to be combined with the electronics on a single chip the compatibility of the two processes such as micromachining and electronics must be considered. These considerations are quite different with the two technologies. For bulk micromachining using anisotropic etchants the compatibility problem is usually with the clean room. If KOH is used, contamination of the wafer surface limits the further processing which can be performed. For surface micromachining the main considerations are often the additional thermal budget of the depositions and annealing and masking during etching. If silicon dioxide is used as the sacrificial layer the corresponding etchant is usually HF based. This creates problems for the aluminum used for metallization. [23]

Microactuators

MEMS enable the development of smart products based on control capabilities of microsensors and microactuators (microvalves, micropumps, optical switches, imaging displays, and microrelays, etc.). Microactuators used one of a variety of integrated actuator mechanisms based on electrostatic, magnetic, piezoelectric, bimetallic, or thermopnumatic phenomena. The microsensors gather information from the environment through measuring mechanical, thermal, biological, chemical, optical, and magnetic phenomena; the microelectronics process the information derived from sensors and, through some decision - making capability, direct the microactuators to respond by moving, positioning, regulating, pumping or filtering, thereby controlling the environment for some desired outcome or purpose. Each of the ones listed above has significant disadvantages, which render them unsuitable for many applications. Many applications require an integrated microactuation mechanism that is compatible with microfabrication, and able to provide a large displacement and a large actuation energy density. [24]

MEMS Packages [25-27]

Packaging of MEMS similar to IC technologies need environmental protection, electrical signal conduit, mechanical support, and thermal management paths. Packaging redistributes electrical signal paths from tight pad dimensions to over larger and more manageable interconnection leads. The mechanical support provides rigidity, stress release, and protection from the environment. Power distribution also needs to be taken into account for optimum packaging scheme. Thermal management is needed to support adequate thermal transport to sustain operation for the product lifetime. [28,29]

Packaging of MEMS is considerably more complex as they serve to protect from the environment, while, somewhat in contradiction, enabling interaction with that environment in order to measure or affect the desired physical or chemical parameters. A package must also provide communication links through optimum interconnect scheme, remove heat through suitable selection of heat sinks, and provide robustness in handling and testing. The materials used for package should be selected to withstand not only handling during assembly and testing, but also throughout the operational environment of the product. Its robustness must be proven in terms of mechanical and thermal shocks, vibration, and resistance to chemical and other conventional life cycling tests especially needed for space applications. [30,31]

The package must also be capable of providing an interior environment compatible with any particular constraints that may affect device performance and reliability. For example, a resonator might need a good vacuum for its operation and packaging scheme need to provide such requirement. MEMS can be integrated with associated electronics on the same chip to produce better electrical output. Integration can be done in the same wafer level or through wafer bonding or utilizing multi-chip module carriers. [5,6,27]

Numerous papers published in literature regarding MEMS packaging issues. For example, Mallon et al., [32] has provided an overview of packaging techniques for silicon sensors and actuators and Frank et al, [33] has provided detailed overview of the packaging tools that are required for sensors. Madou [11] has discussed a variety of process issues associated with the packaging of MEMS. Senturia and Smith [34] have highlighted the importance of system partitioning, package design and process optimization when building the electronic components and sensor structures as part of the single device. Reichl [35] have described the requirements for packaging technologies, bonding techniques, chip-substrate interconnection techniques, and alternative chip integration techniques to deliver reliable, economical, and application specific solutions by choosing optimized technologies and appropriate materials combinations.

Kim [36] has described packaging scheme of pressure sensor arrays utilizing multi-chip modules and tape automated bonding (TAB) carrier. This one was developed specially for aerospace and aircraft applications thus requiring thin profile packaging with high accuracy.

Schmidt [5] has described the advantages of wafer-to-wafer bonding to realize tremendous savings in cost since this enables this packaging of a multitude of sensors or actuators simultaneously, eliminating costly individual chip-packaging steps and enhancing the higher performance.

Weiller et al., [26] have developed a spaceflight testbed for chemical mcirosensors and microsystems designed to fly on the space shuttle. The sensors integrated into this experiment include a micromachined interferometer for carbon dioxide detection, a palladium-based sensor for hydrogen, a micromachined micro hot plate sensor for carbon monoxide, and micromachined strain gauge pressure sensor, and networkable digital thermometers.

Interconnections

MEMS packaging must first protect the micromachined parts in broad-ranging environments; it must also provide interconnects to electrical signals, and, in some cases, access to and interaction with the external environment. For example, the packaging of a pressure sensor must ensure that the sensing device is in intimate contact with the pressurized medium, yet protect from harsh environments. Packaging of valves must provide both electrical and fluid interconnects. Therefore, the standards, for MEMS are lacking and designs became proprietary. Large dimensions of packages tend to dilute the small size advantage of MEMS and it is also very expensive 75 – 95% of the overall cost of MEMS systems. The design of the package and of the micromachined structures must commence and evolve together. In hermetic packages the electrical interconnections through a package must conform hermetic sealing. In ceramic packages, metal pins are embedded and brazed within the ceramic laminates. For metal packages, glass firing yields a hermetic glass-metal seal. Even deionized water can leach out phosphorous from low-temperature oxide (LTO) passivation layers to form phosphoric acid which, in turn, etches and corrodes aluminum wiring and bond pads. [37]

Die-attach Processes

Subsequent to dicing of the substrate, each individual die is mounted inside a package and attached (bonded) onto a platform made of metal or ceramic, though plastic is also possible under limited circumstances. Careful consideration must be given to die attaching because it strongly influences thermal management and stress isolation. Naturally, the bond must not crack over time or suffer from creep. Its reliability must be established over long periods of time. Die-attach processes employ metal alloys or organic or inorganic adhesives as intermediate bonding layers. Metal alloys are comprised of all forms of solder, including eutectic and noneutectic. Organic adhesives consist of epoxies, silicones, and polyimides. The choice of a solder alloy depends on its having a suitable melting temperature and mechanical properties. A solder firmly attaches the die to the package and normally provides little or no stress isolation when compared with organic adhesives. However, the bond is very robust and can sustain very large, normal pull-forces. The large mismatch in the coefficients of thermal expansion with silicon or glass results in undesirable stress that can cause cracks in the bond. [38]

Wiring and Interconnects

Electrical connectivity provides electrical interconnection between the die and electrical component external to it. The fluid connectivity is to ensure the reliable transport of liquids and gases between the die and external fluid control units.

Electrical Interconnects

Wire bonding is popular technique to electrically connect the die to the package. The free ends of a gold or aluminum wire form low-resistance (ohmic) contacts to aluminum bond pads on the die and to the package leads or terminals. Bonding gold wires tends to be easier than bonding aluminum wires. Theromsonic gold bonding is a well-established technique in the IC industry, simultaneously combining the application of heat, pressure, and ultrasonic energy to bond area. Ultrasound causes the wire to vibrate, producing localized frictional heating to aid in the bonding process. Typically, the gold wire forms a ball bond to the aluminum bond pad on the die, and a stitch bond to the package lead. The temperature of the substrate is usually near 150°C, below the threshold of producing Au-Al intermetallic compounds that cause bonds to brittle. One of these compounds is known as purple plague and is responsible for the formation of voids by the diffusion of Al into gold. Bonding of Al wires to Al bond pads is also achieved with ultrasonic energy, but without heating the substrate. A stitch bond works better than a ball bond, but the process tends to be slow. This makes bonding aluminum wires not as economically attractive as bonding gold wires. However, gold wires with diameters above 50 μm are difficult to obtain, which makes Al wires, available in diameters up to 560 μm, the only solution for high current applications. The use of wire bonding runs into serious limitations in MEMS packaging. For instance, the applied ultrasonic energy, normally at a frequency between 50 and 100 kHz may stimulate the oscillation of suspended mechanical microstructures. Unfortunately most micromachined structures coincidentally have resonant frequencies in the same range, increasing the risk of structural failure during wire bonding. [37]

Flip-chip Technologies

Flip-chip bonding involves bonding the die, top-face-down, on a package substrate. Electrical contacts are made by means of plated solder bumps between bond pads on the die and metal pads on the package substrate. The attachment is intimate with relatively small spacing (50 – 200 μm) between the die and the package substrate. Unlike wire bonding which requires that bond pads are positioned on the periphery of the die to avoid crossing wires, flip-chip allows the placement of bond pads over the entire die (area arrays) resulting in a significant increase in density of input/output (I/O) connections. The effective inductance of each interconnect is miniscule because of the short height of the solder bump.

Flip-chip bonding is attractive to the MEMS industry because of its ability to closely package a number of distinct dice on a single package substrate with multiple levels of embedded electrical traces. For instance, one can use flip-chip bonding to electrically connect and package three accelerometer dice, a rate sensing, and ASIC onto one ceramic substrate to build a fully self-contained navigation system. This type of hybrid packaging produces complex systems, though each individual component in itself may not be as complex. A similar system can be built with wire bonding, but its area usage will not be as efficient, and its reliability may be questionable given the large number of gold wires within the package. Flip-chip may not compatible with the packaging of MEMS that includes microstructures exposed to the open environment. For instance, there is a risk of damaging the thin diaphragm of a pressure sensor during a flip-chip process. Capped devices can take full advantage of flip-chip technology. [37]

Microfluidic Interconnects

Electrical interconnects technology derives from the packaging requirements of the integrated circuit industry, but that is not the case for fluid interconnects. These are required to package microfluidic devices such as micropumps and microvalves.

Ceramics Packaging

Ease of shaping along with reliability and attractive materials properties (e.g., electrical insulator, hermetic sealing) have made ceramics mainstay in electronic packaging. They are widely used in multichip modules and advanced electronic packages such as ball grid arrays. These same characteristics have extended the utility of ceramics to the packaging of MEMS. Many commercially available micromachined sensors use some form of ceramic packaging. Ceramic packaging is significantly more expensive to other materials. [37]

Metal Packaging

In the early days of the integrated circuit industry, the number of transistors on a single chip, and the corresponding pin count (number of input/output connections) were few. Metal packages were practical because they were robust and easy to assemble. Metal packages are attractive to MEMS for the same reasons the integrated circuit industry adopted the technology in the early days. They satisfy the pin-count requirements of most MEMS applications; they can be prototyped in small volumes with rather short turnaround periods; and they are hermetic when they are sealed. They are more expensive to plastic packages. Packaging solutions for harsh environments (aerospace and other industries) can be complex and costly. Packaging for harsh environments has been an art since there is a lack of market demand. [37]

Molded Plastic Packaging

Molded plastic packages are not hermetic unlike metal and ceramic. They dominate in the packaging of integrated circuits because they are cost effective solutions. Advances in plastic packaging have further improved reliability to high levels. There are two general approaches to plastic packaging such as postmolding and premolding. The molding process is a harsh process which involves melting the thermosetting plastic at 175°C, then flowing it relatively under high pressure (~ 6 Mpa) into the mold cavity before it is allowed to cool. The temperature cycle gives rise to sever thermal stresses, due to the mismatch in coefficient of thermal expansion between the plastic, the lead frame and die. These stresses may damage the die, or cause localized delamination of the plastic. [37]

MEMS Packaging Using MCMs

Multichip modules achieve many of the benefits of monolithic integration by combining a number of different integrated circuit dies, usually from different wafers and process technologies, on a common host substrate. Hence, MCMs offer attractive approach to integrating and packaging MEMS because of their ability to support MEMS and microelectronics on a common substrate without requiring changes in or compromises to the native fabrication processes. In a patterned substrate MCM, the dies are located above the host substrate and the interconnection between dies is made through wiring on the substrate. Patterned overlay is an alternate approach to MCM packaging in that the dies are embedded in the substrate and interconnects between dies are made via an overlay fabricated on top of the dies. Interconnection between dies can be made using variety methods such as wirebonding, flip-chip solder bumps, and direct metallization. Close proximity of the dies allows for improved system performance by providing low-noise wiring and eliminating unnecessary interconnections. Key considerations for MCM packaging of MEMS include whether to release the micromachined devices before or after packaging and the compatibility of the package materials with the MEMS release procedures. Most MEMS devices require a 'release' etch prior to operation use. The release process involves removing selected materials to create three-dimensional structures and, in some cases to allow physical movement. Released MEMS devices are typically very fragile and require special handling. Consequently, it is desirable to release the devices after packaging especially when using foundries. However, many of the release etchants commonly used for MEMS are harmful to microelectronics and microelectronic packaging.

The most serious problem discovered during postpackaging analysis of the surface micromachined test die was the potential for MEMS devices warping or failure due to excessive heating from laser ablation. Devices most susceptible to overheating were long, thin structures with poor heat loss paths of the substrate. Polysilicon resistors in areas that received high laser ablation power also showed resistance drops of 10 – 15%. Moreover, devices in smaller ablated windows were also more likely to show thermal damage from laser ablation. [39]

Integrated Monolithic MEMS

Integrated systems are defined as batch-fabricated interconnections of complex digital integrated circuits with analog interface circuits and transducers such as sensors. The advantages of fully integrated MEMS that merge microstructures and microelectronics on a single substrate are reduced size, electronic noise, and system power. There are often significant challenges to success with monolithic processing. These challenges include materials and process incompatibilities and the greater cost of special-purpose electronic processes compared with conventional digital CMOS. A hybrid approach with separate MEMS and electronic chips remains competitive approach. Hybrid packaging of MEMS has been demonstrated using MCM and flip chip technologies. [40,41] A number of examples of monolithically integrated MEMS have been described [42-48] to achieve a monolithic MEMS technology.

MEMS Reliability [9,10,49-51]

Reliability requirements for various MEMS will be significantly different from one application to another especially where the systems incorporating MEMS components are unique. Standardized reliability testing is not possible until common set of reliability requirements is developed. Literature survey on MEMS reliability issues produced limited information but valuable results.

Romig et al, [52] identified a list of packaging reliability concerns for microsystems. Factors mentioned that affect the MEMS packaging included tribological behavior, contamination, cleaning stiction, and typical mechanical fatigue issue. [53,54] Brown et al, [55] reported characterization of MEMS fatigue on polysilicon. Reliability assessment for media compatibility for a gas sensor produced coating requirement [56] while a need for new device passivation and alternative chip mounting techniques was identified by Dyrbye et al. [57]

Miller et al, [58] reported reliability testing of surface micromachined microengine whose analysis concluded the prevailing failure mode was the gear sticking to the substrate or to the hub and showed that significant portion of the microengine failure was infant mortality. [51,53] In another paper, Tanner et al, [59] observed a large amounts of debris in the areas of microengine rubbing which led to the failure of drive gears. They have also presented qualitative and predictive model for actuator reliability. In their recent study, the effect of moisture content on failure by wear mechanism was determined. It was shown that as the humidity decreased the volume of debris generated increased. For the higher humidity levels, the formation of surface hydroxides considered to act as a lubricant resulting in lower amounts of wear debris. [60] Patton et al, [61] also showed the effect of humidity on failure mechanism for MEMS electrostatic lateral output motor. Electrical performance degraded with increased humidity whereas mechanical seizure showed mixed results. At a very low and high humidity, failure occurred mechanically and electrically, respectively, whereas improvement observed below and above 40% RH. Kelly et al, [62] have described the issues how packaging influence the reliability and performance characteristics of MEMS.

Kohler et al., [30] have discussed the strategy towards bond qualification in silicon microsystems by using Weibull statistical approach. The results have shown that the degradation of fracture toughness in bonded microsystems during vibration and thermal cycling.

Lyke [25] has emphasized the importance of packaging in realizing the efficiencies promised by the MEMS devices. Packaging must provide the environment necessary to sustain the proper operation of MEMS devices. For almost all MEMS designs, fabrication of an integrated design, while meeting the requirement of MEMS device release chemistry is challenging.

Connelly et al., [31] have described inertial MEMS sensors development for space applications. Inertial sensors represent the important segment of an emerging MEMS technology. Draper labs have been developing miniaturized micromachined gyroscopes and accelerometers for over 10 years. Draper has transitioned this technology under an alliance agreement with Boeing. Boeing is now in pilot production to meet the automotive market demand.

JPL has been very active in MEMS characterization and their implementation for aerospace applications. For example, an extensive reliability testing of MEMS devices especially for space applications was done by Muller et al, [63] who provided a comparison for testing environments for space applications with automotive environment. Tang et al, [64] have described extensively on design, fabrication, and packaging of a silicon MEMS vibratory gyroscope for microspacecraft applications. Miller et al, [65] have described an overview of MEMS development for micro- and nano-spacecraft application and emphasized the reliability, packaging, and flight qualification methodologies that need to be developed for MEMS to produce robust MEMS for space applications. Hartley [66] discussed the requirements of a nano-g accelerometer developed by NASA in collaboration with Northeastern University for the tri-axial measurement of orbital drag on the Shuttle and Space Station. It required an acceleration range of 10^{-2} to 10^{-8} g over a frequency range of 0.001-25 Hz.

COTS MEMS Applications

The maturest MEMS devices are pressure sensors and accelerometers. The manifold absolute pressure (MAP) sensor has been used in automobile industry since 1979. [67] Today many automobiles have one of these sensors in their electronic engine control system. Pressure sensors also widely used for medical invasive blood pressure sensor applications. Accelerometer is being used for an airbag crash sensor in automobile since 1990. In addition to significant mass reduction, the integration of diagnostic characteristics into sensors, enable device internal failure detection.

Micromachined accelerometer includes mechanical flexure-supported masses and assembled sensors. The sensor is assembled via integration and then in a closed-rigid package. The sensor consists of a set of fixed beams and a moveable beam structure to sense relative movement. The beam to beam closeness could cause stiction. Hartzel et al, [68] developed a methodology for prediction of stiction-related field failures.

Spangler [69] presented development of IC package for micromachined accelerometer for automotive applications. In their recent developmental activities, the use of surface mountable package rather than single in line through package (SIP) was engineered. The surface mountable device (SMD) version gave more life to the existing die product and at the same time, that has met requirements for surface mount components.

MEMS Reliability and Key Failure Mechanisms [5-10,18,19,27,28,30,31,49,50,51,53]

Almost all cited reliability-testing issues were summarized for a certain application and cannot usually be used for any other application to benchmark. Understanding of MEMS reliability and technology assurance issues are key to their wider acceptance towards high reliability applications as well as technology transfer their commercialization. MEMS reliability is one of the most difficult questions to answer since they are still in their infancy, developed for specific applications, and reliability requirements vary and finally, which frequently depend on the user requirements. In spite of differences, similar common methodologies could be developed for assessing qualification and reliability for those with similar failure mechanisms. [26,30]

A critical part of understanding the reliability of any system comes from understanding the system failure behavior and their mechanisms. For IC package assembly, failure generally related to solder joint. [2] In MEMS, there are several failure mechanisms that have been found to be the primary sources. These include:

- Failure by Stiction and Wear: Contrary to solder joint failure for IC system failure, thermal cycling fatigue failure for MEMS are of less critical. Stiction and wear, however, are real concern and cause most failures for MEMS. MEMS failure may occur due to microscopic adhesion when two surfaces are come into contact which is called stiction. Microscopic separations generally induce particulate which when caught between micro parts will stop part movement. Wear due to corrosive environment is another aspect of such failure.
- Delamination: MEMS may fail more often due to delamination than IC systems since there are much wider bonding applications. For example, delamination of bonded thin film materials, and bond failures of dissimilar and similar materials such as wafer-to-wafer bonding.
- Environmentally induce failures: Failure due to thermal cycling, vibration, shock, humidity, radiation effect, etc. are commonly observed for MEMS and IC packaging systems. MEMS devices because of having additional mechanical moving parts, are more susceptible to environmental failure than their IC packaging systems.
- Cyclic mechanical fatigue: This is critical for comb and membrane MEMS devices where materials are subjected to alternative loading. Even if the load is such that it is significantly below failure, the stress can cause degradation in materials properties. For example, changes in elastic properties affect resonant and damping characteristics of beam and therefore degrade MEMS sensor outputs.
- Dampening Effect: Dampening is not critical for IC packaging, but it is critical for MEMS devices, which operate with moving parts at their resonant frequency. Dampening can cause by many variables including presence of gas in atmosphere. Therefore, good sealing is essential for avoidance of such failure.
- Packaging: Packaging and development of testing methodologies and understanding their failure mechanisms including vacuum packaging of Infrared (IR) MEMS uncooled detectors and arrays, as well as, inertial MEMS accelerometers and gyros, and radio frequency (RF) resonators are key issues in the technology development path to low cost, high volume MEMS production.

COTS MEMS Program

It is apparent that a single set of reliability testing requirements for a wide application may not be possible for evaluation of MEMS technology. However, finding a common denominator and standardized testing based on the MEMS key failure mechanisms are valuable to user community. The users can carry out then any additional reliability testing specifically needed for their applications thus minimizing the cost of new technology implementation. The standardized test methodology when developed will also reduce unclear communication between users and suppliers thus avoiding any unnecessary expenses. We consider that it will be easier to start with high volume COTS type MEMS components, which have potential for high reliability application. In addition, because of their availability and lower cost, a large number of these components can be tested to generate statistically meaningful reliability data.

JPL has initiated COTS MEMS program with the objectives of understanding quality and reliability assurance associated with implementation of this technology and help to build needed infrastructure. Similarly, to COTS IC packaging program [1,2], it is intended to form an industry-wide consortium from aerospace, military, and commercial sectors. Consortium will emphasize development of test methodologies for characterizing reliability of COTS pressure sensors and accelerometers. Both these technologies were used and being considered for high reliability applications. For example, a COTS MEMS micromachined accelerometer was used for NASA-JPL Mars Microprobe, which launched in January 3, 1999 aboard the international Mars Polar Lander. [65] A COTS MEMS pressure sensor is also being evaluated at NASA Glenn Research Center for measuring airflow of inlet compressor of a turbofan propulsion system. [70]

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